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EFFECTS OF TRAVELING MAGNETIC FIELD ON DYNAMICS OF SOLIDIFICATION

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PROJECT OBJECTIVES

The objectives of this work are:

1) to develop theoretical and experimental fundamental features of the traveling magnetic field (TMF) technique, with the aim of identifying its benefits for microgravity research on solidification processing
2) to determine the influence of a traveling magnetic field on the following selected technologies:
   a) crystal growth of semiconductor materials by Bridgman and Float Zone techniques
   b) mixing of metal alloy melts prior to solidification

TMF is based on imposing a controlled phase-shift in a train of electromagnets, forming a stack. Thus, the induced magnetic field can be considered to be travelling along the axis of the stack. The coupling of this traveling wave with an electrically conducting fluid results in a basic flow in a form of a single axisymmetric roll. The magnitude and direction of this flow can be remotely controlled. Furthermore, it is possible to localize the effect of this force field though activating only a number of the magnets. This force field generated in the fluid can, in principle, be used to control and modify convection in the molten material. For example, it can be used to enhance convective mixing in the melt, and thereby modify the interface shape, and macrosegregation. Alternatively, it can be used to counteract thermal and/or solutal buoyancy forces. High frequency TMF can be used in containerless processing techniques, such as float zoning, to affect the very edge of the fluid so that Marangoni flow can be counter balanced.

The proposed program consists of basic fundamentals and applications. Our goal in conducting the following experiments and analyses is to establish the validity of TMF as a new tool for solidification processes. Due to its low power consumption and simplicity of design, this tool may find wide spread use in a variety of space experiments. The proposed ground based experiments are intended to establish the advantages and limitations of employing this technique.
In the fundamentals component of the proposed program, we will use theoretical tools and experiments with mercury to establish the fundamental aspects of TMF-induced convection through a detailed comparison of theoretical predictions and experimental measurements of flow field. In this work, we will conduct a detailed parametric study involving the effects of magnetic field strength, frequency, wave vector, and the fluid geometry.

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The applications component of this work will be focused on investigating the effect of TMF on the following solidification and pre-directional solidification processes:

1) Bridgman growth of Ga:Ge with the goal of counteracting the buoyancy-driven convection
2) Mixing of Pb-Ga and Pb-Sn alloys with the aim of initiating and maintaining a uniform melt prior to solidification processing
3) Float Zone growth with the aim of identifying, through simulations and model experiments, conditions needed to counteract Marangoni flow in a microgravity environment.

The proposed research has strong relevance to microgravity research and the objectives of the NRA. TMF can provide a unique and accurate mechanism for generation and control of desirable flow patterns for microgravity research. These attributes have significant relevance to 1) Alloy mixing prior to solidification in a microgravity environment. TMF can provide this mixing with a low level of power consumption. 2) TMF can offset the deleterious effects of Marangoni convection in microgravity containerless processing. Thus, TMF can be instrumental in further understanding this phenomena. 3) Generation of controlled flows will allow the investigation of the effect of these flows on growth morphology and growth kinetics. 4) On Earth, TMF has the potential to significantly counter-balance thermosolutal convection, thereby creating conditions similar to those obtained in microgravity.

Once demonstrated, this new tool for use in solidification has the strong potential to find applications in a host of microgravity material research projects.

I. Basics of Traveling Magnetic Field Technique

Externally imposed temperature and/or solutal gradients are inherent to crystal growth processes. On Earth, these gradients induce convection in the melt from which the crystal is grown. This buoyancy or solutal driven convection can degrade micro- and macroscopic homogeneity and increase the defect concentration in the grown materials. For these reasons, over the past twenty-five years or more, considerable research has been focused on controlling convection. One approach is to grow the material in a microgravity environment to reduce the primary driving force for convection. Another is to apply static magnetic fields to the electrically conductive melts to oppose convection by the induced Lorentz force. Recently, a new concept to control convection by utilizing magnetic fields that are variable in time and space has been put forward, *i.e.*, the rotational magnetic field (RMF). In electrically conducting melts enclosed in cylindrical containers RMF induces liquid motion consisting of a swirling basic flow and a meridional secondary flow. This flow has been found to be beneficial for several applications. It allows increase in crystal growth rate, and improves its homogeneity and quality [1,2]. RMF can also be used for mixing non-homogeneous melts in continuous metal castings [3]. These applied aspects have stimulated increasing research on RMF-induced fluid dynamics [10-23]. We have recently proposed yet another type of magnetic field configuration, that may find use in crystal growth techniques such as vertical Bridgman (VB), float zone (FZ), and the traveling heater method (THM) [4-9]. We termed it traveling magnetic field (TMF) as it consists of an axisymmetric magnetic wave. The frequency of this wave is sufficiently low, so that the variable in time magnetic field induces a negligible electric field in free space (no electromagnetic waves). Essentially, a controlled phase shift in a train of electromagnets induces a traveling magnetic wave. This wave, when coupled to an electrically conductive fluid, will result in a basic flow having the form of a single axisymmetric roll. The magnitude and direction of this flow can be remotely controlled and used to control and modify convection in a molten semiconductor material. It can be used to either enhance or counteract existing convection, thereby influencing the solid/liquid interface morphology, as well as micro- and macro-segregation. TMF can be useful also in homogenizing melts prior to solidification, an especially useful feature when processing in a microgravity environment.

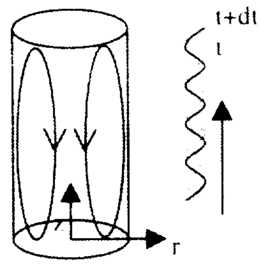


Figure 1. Schematic of TMF

Crystal growth techniques such as VB, FZ or THM utilize, as a rule, cylindrical ampoules. Mass transport is thus predominantly in the axial direction. In order to modify this process, a meridional flow can be used. Although RMF induces such a flow, it is not a basic flow but a secondary one due to nonlinear effects. Therefore, its properties are difficult to assess and its control is problematic, especially since a useful level of this flow will be close to the unstable time dependent region. Also, the direction of the meridional flow cannot be changed. It would be desirable to directly control meridional flow by a suitable body force as can be induced by TMF. This method consists of applying an axisymmetric magnetic wave along the axis of the ampoule containing the molten material. In order to accomplish this, a set of coils is wound around the ampoule. The coils are powered by ac current with predetermined phase offsets between sections. The geometry of this method is depicted in Figure1. In the low frequency approximation, the vector potential of the applied magnetic field can be expressed using a modified Bessel function as [4-9]:

$$\mathbf{A} = \mathbf{e}_\varphi \frac{B_0}{a} I_1(ar)\sin(\omega t - az). \quad (1)$$

Then the following set of equations in cylindrical coordinates is obtained:

$$\frac{\partial w}{\partial t} = \left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{1}{r^2} + \frac{\partial^2}{\partial z^2}\right]w + \frac{v_r w}{r} - \left(v_z\frac{\partial}{\partial z} + v_r\frac{\partial}{\partial r}\right)w - Ha^2 I_0^2(ar)\frac{\partial v_r}{\partial z}$$
$$+ \frac{\partial}{\partial r}\left(\left(Ha^2 v_z - \frac{Tm}{a}\right) I_1^2(ar) - Ra\theta\right) \quad (2a)$$

$$P\left(\frac{\partial \theta}{\partial t} + v_r\frac{\partial \theta}{\partial r} + v_z\frac{\partial \theta}{\partial z}\right) = \nabla^2\theta \quad (2b)$$

Here vorticity is represented by the first equation with the second being the heat transport equation, needed later for demonstration of the effects of TMF on buoyancy convection. The equations are written in non-dimensional units (primes are dropped) and the adopted scaling is as follows: time $t = t' r_0^2/\nu$, velocity $v = v'\nu/r_0$, vorticity $w = w'\nu/r_0^2$, Rayleigh number $Ra = \frac{\beta g r_0^3 \Delta T}{\nu\kappa}$, Prandtl number $P = \frac{\nu}{\kappa}$, and Tm, Ha are defined by

$$Tm = \frac{B_0^2 \sigma \omega r_0^4}{2\rho\nu^2}, \quad Ha = \sqrt{\frac{B_0^2 \sigma r_0^2}{2\rho\nu}}.$$

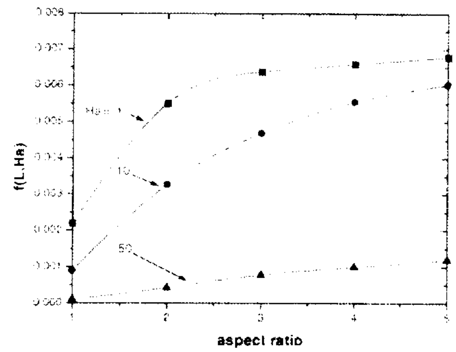


Figure 2. Plot of f as a function of aspect ratio for three values of Hartman number.

A steady state version of the set of equations (2) was numerically analyzed [7]. For small Hartmann numbers, $Ha<1$, and for small magnetic Taylor numbers, $Tm<1000$, a vector plot of the meridional flow is displayed in Figure 4 (left) and it represents a single axi-symmetric roll. With increasing Hartmann number (>10), the center of the roll is pushed towards the corner. For the linear regime (approximately $Tm<10^4$), the maximum value of the flow can be estimated as:

$$|V|_{max} = Tm\frac{\nu}{r_0}\, f(\,L,Ha\,) \tag{3}$$

where $L=h/r_0$ is the aspect ratio. A plot of the function $f(L,Ha)$ is given in Figure 2. Consider, as an example, when a magnetic field of 5 gauss and 50 Hz is applied to the column of mercury having a 1cm radius and 10 cm length. Approximate values of Ha=0.1, Tm=2000, and V_{max}=0.2mm/sec are obtained. Note that this is a significant velocity for crystal growth applications. Non-linearity in the transport equations (2) shows up for values of $Tm > 1000$. Essentially, it modifies the shape of the meridional roll. As Tm increases, the center of this roll drifts from the middle of the cylinder to the bottom, for the case of TMF propagating upwards. A contour plot of the stream function for the rather significant value of $Tm=10^5$ and for $Ha=1$ is displayed in Figure 3. The maximum of the stream function as a function of Tm, varies linearly for $Tm<1000$, after which a slight bowing effect is visible. Behavior then can be approximated by the power functional relation $Tm^{0.84}$.

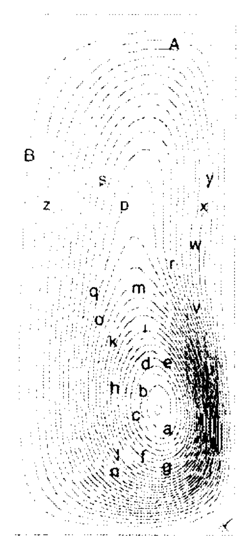
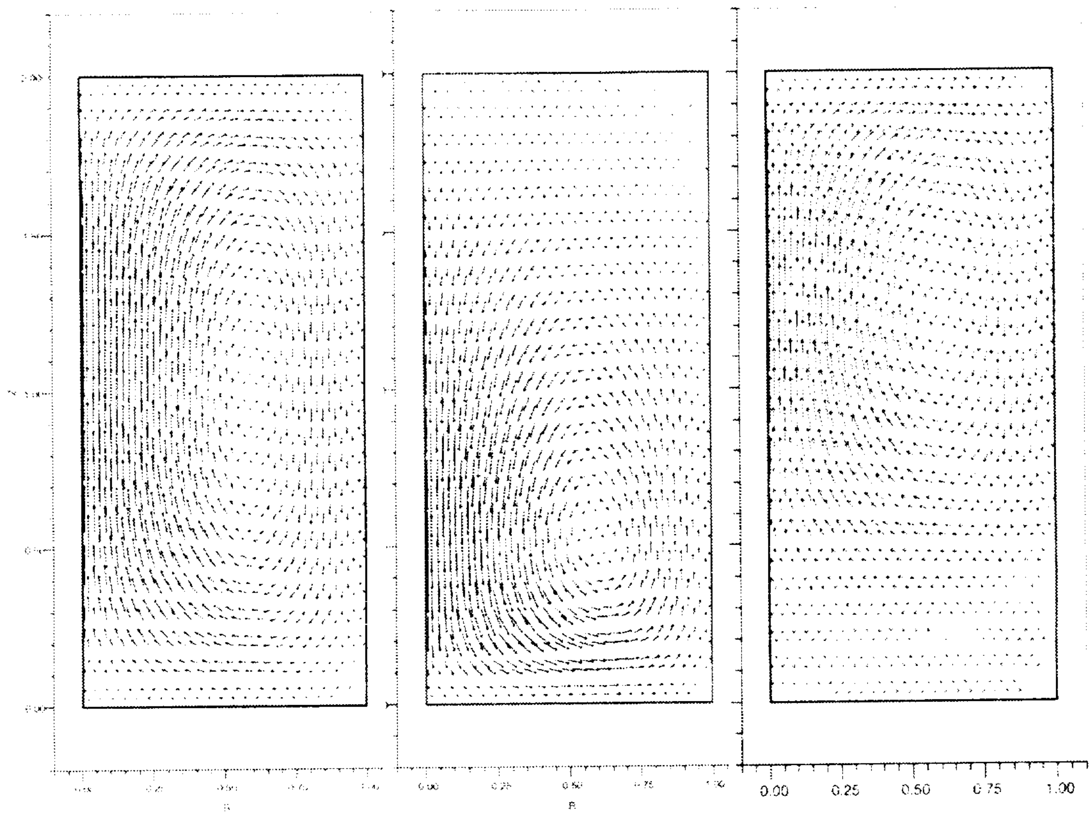


Figure 3. A contour plot of the stream function for TMF.

Now consider the possibility of reducing thermoconvective flow. The driving forces from TMF and buoyancy can be partially cancelled by appropriate selection of the Tm value. For illustration purposes,



TMF Buoyancy TMF+Buoyancy

Figure 4. Flow patterns generated by a TMF, buoyancy, and a TMF and buoyancy combined.

we consider a thermal field with the following boundary conditions: linear variation of temperature along the side wall, quadratic in r at the bottom of the cylinder, and constant at the top. Without TMF, buoyancy resulting from the thermal field leads to the convective flow pattern depicted in Figure 4 (center) (Ra=10, P=1). When both TMF and buoyancy are included in the calculation, then for a certain Tm, the flow can be significantly reduced at the bottom of the cylinder as seen in Figure 4 (right). This type of flow circulation can be beneficial for crystal growth.

A simple prototype of the TMF generator has been recently constructed and test velocity measurements were performed [4]. The experimental setup consists of a cylindrical column of mercury, 3.17 cm in diameter and 12 cm in height, that is placed into the TMF set of coils. The anemometer response to the TMF for three values of applied power is presented in Figure 5. For the first 100 seconds there is no field (zero flow), for the next 5 minutes followed by a field of 3.5 gauss (rms). This is then followed by a 7 minute application of a 7.2 gauss field and, subsequently, to a 14 gauss field for 3.5 minutes The clear transition from quasi-steady flow (3.5 gauss) to oscillatory and subsequently chaotic flow as the

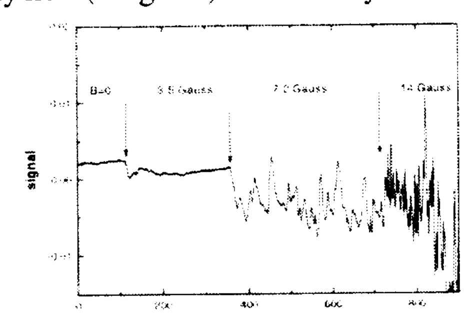


Figure 5. The anemometer response to the TMF for three values of applied power.

magnetic field strength is increased is evident. The observations of the flow character indicate that the transition to time-dependent flow occurs at approximately $Tm_{crit}=10^4$. Incidentally, this value is close to the one for the onset of oscillations in a rotational magnetic field geometry (aspect ratio 4:1).

II. Summary

A brief exposition of the TMF method has been presented. In essence, TMF induces a single axisymmetric vortex in circular cylinders filled with electrically conducting melts. The magnitude and direction of this flow can be remotely and easily controlled. When superimposed on the buoyancy force, the combined body force can be much smaller than the initial buoyancy force. This can result in substantially smaller and laminar steady-state flow. Such flow conditions in the vicinity of the growing crystal interface can be beneficial for its quality. Obvious TMF applications include VB and THM configurations. In the float zone method, surface tension driven convection can be modified by a suitable localized high frequency TMF. Alloy mixing prior to solidification can yet be another useful application of the TMF. Here flow along the axis of the ampoule induced by TMF can mix melts in a short time. RMF, as a competitive mixing method, is much less effective for long ampoules, as only two adjacent to the end cups vortices could promote axial mixing.

A theoretical model of the Lorentz force of arbitrary frequency induced in finite cylinders has been developed in [6]. Modeling of flow dynamics induced by this force has been conducted in [7], and preliminary experimental data on TMF can be found in [4,8,9].

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